

# Effect of Heat Exchanger Configuration on the Performance of Joule-Thomson Refrigerators

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## ABSTRACT

A typical Joule-Thomson (J-T) refrigerator consists of a recuperative heat exchanger, a gas expansion nozzle, a mandrel, and a compressed gas storage bottle. The thermodynamic performance of a J-T refrigerator depends highly on the hydraulic and heat transfer characteristics of the recuperative heat exchanger. The typical recuperative heat exchanger of a J-T refrigerator has a double helical tube and fin configuration, but other heat exchanger configurations may be used, including the two-flow type helical tube and fins configuration, the two-stage heat exchanger configuration, a double helically wound tube circuit arranged in a spiral channel, etc.

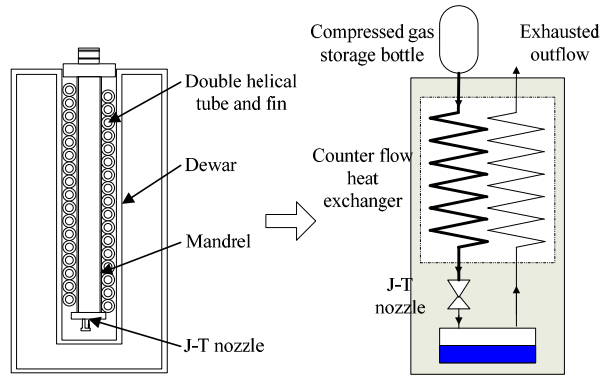
In this study, the performance of J-T refrigerators with single and two-flow type recuperative heat exchangers was investigated. The effectiveness-NTU approach was adopted to predict the thermodynamic behaviors of the heat exchangers for the J-T refrigerators.

The results show the effect of the operating conditions on the performance of the heat exchanger and refrigerator for three types of heat exchangers. The influences of mass flow rate and supply pressure on the effectiveness of the heat exchanger and the refrigeration power are discussed in detail.

## INTRODUCTION

Miniature Joule-Thomson (J-T) refrigerators have been widely used for rapid cooling of infrared detectors, probes for cryosurgery, thermal cameras, missile homing heads, and guidance systems. This wide utilization is due to their special features of simple configuration, compact structure, and rapid cool-down. Nitrogen (NBP 77.35K) and argon gas (NBP 87.3K) are typically used as the cryogen due to their availability, low cost, and their ability to achieve a relatively low cryogenic temperature.

The cool-down time, temperature at the cold end, running time, and gas consumption are the important indicators of the performance of a miniature Joule-Thomson refrigerator.



**Figure 1.** Schematic diagram of a Joule-Thomson refrigerator

A typical Joule-Thomson refrigerator consists of a recuperative heat exchanger, a gas expansion nozzle, a mandrel, and a compressed gas storage bottle as shown in Figure 1. The cooling power of the J-T refrigerator is generated by the isenthalpic expansion of the high pressure gas through a throttling process. The J-T cooling effect can be amplified by using the expanded gas to cool the incoming gas within a recuperative heat exchanger.

The thermodynamic performance of a J-T refrigerator depends highly on the hydraulic and heat transfer characteristics of the recuperative heat exchanger. The typical recuperative heat exchanger of a J-T refrigerator has a double helical tube and fin configuration, but other heat exchanger configurations may be used, including the two-flow type helical tube and fins configuration, the two-stage heat exchanger configuration, a double helically wound tube circuit arranged in a spiral channel, etc.<sup>1</sup>

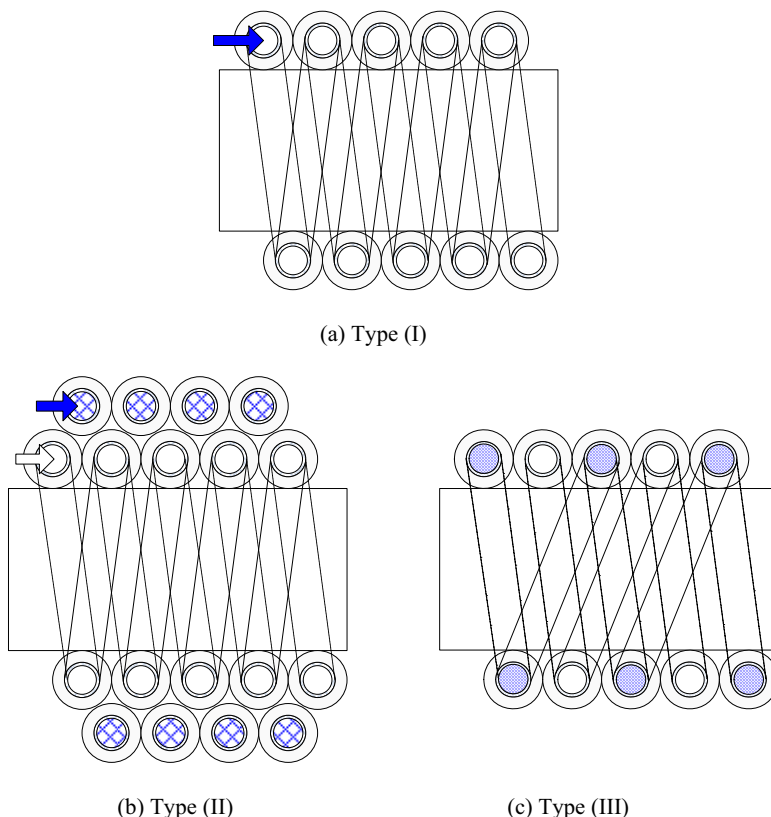
Ng et al.<sup>2</sup> and Xue et al.<sup>3</sup> have conducted steady state simulations of the Hampson-type heat exchanger with argon gas. The performance of the Hampson-type heat exchanger was evaluated for its effectiveness, flow, and heat conduction losses, as well as its liquefied yield fraction. Chua et al.<sup>4</sup> developed an analytical model of the Hampson-type cryocooler with argon gas, and the steady state governing equations were solved numerically. Hong et al.<sup>5</sup> adopted the effectiveness-NTU approach to predict the thermodynamic behavior of the heat exchanger of a J-T refrigerator for different pressures and mass flow rates of nitrogen and argon gas.

In this study, the performance of J-T refrigerators with single and two-flow type recuperative heat exchangers was investigated. The effectiveness-NTU approach was adopted to predict the thermodynamic behavior of the heat exchangers.

## RECUPERATIVE HEAT EXCHANGER

Finned tube heat exchangers have been the most common way of constructing J-T refrigerators. The heat exchanger is formed by wrapping the finned tube around an inner sheath tube (mandrel). A polyester thread is co-wound above the finned tube to provide spacing and to direct flow to the finned tube. The number of wraps determines the overall length of the heat exchanger.

The configuration of the external finned side primarily determines the effectiveness of the counter-flow heat exchanger. The pressure drop across the length of the expanded gas side affects the temperature at the nozzle. Increasing the pressure drop increases the saturation pressure and the temperature of the nitrogen gas. The heat exchanger should be designed to minimize the pressure drop of the expanded gas, thus insuring a refrigeration temperature of 80 K or less. Considerations that influence the pressure drop of the low pressure gas are the flow area, the mass flow rate, thermodynamic properties of the working fluid, and the overall length of the heat exchanger.<sup>6</sup>



**Figure 2.** Configuration of heat exchangers.

A heat exchanger can be built with two passages for the high pressure gas and a common passage for low pressure gas. Several layers of tubes may be used to provide multiple parallel paths for the high pressure gas, thereby reducing the pressure drop.

In this study, the performance of J-T refrigerators with single and two-flow type recuperative heat exchangers was investigated. Configurations of the heat exchanger are shown in Figure 2. Type (I) has a conventional double helical tube and fin configuration. Types (II) and (III) have two passages for the high pressure gas, and the surface area of the finned tubes is double that of the type (I) with the same number of wraps. The overall length of the heat exchanger of the type (III) is double that of the type (I) and (II) with the same number of wraps.

The geometric dimensions of the recuperative heat exchangers are listed in Table 1. The analysis was carried out for nitrogen gas with an inlet pressure of 10 ~ 50 MPa and at 295 K.

**Table 1.** Dimensions of a recuperative heat exchanger

Parameters	Value
Inner diameter of tube	0.3 mm
Outer diameter of tube	0.5 mm
Pitch of tube	1.1 mm
Fin (height/thickness)	0.2 / 0.08 mm
Pitch of fin	0.3 mm

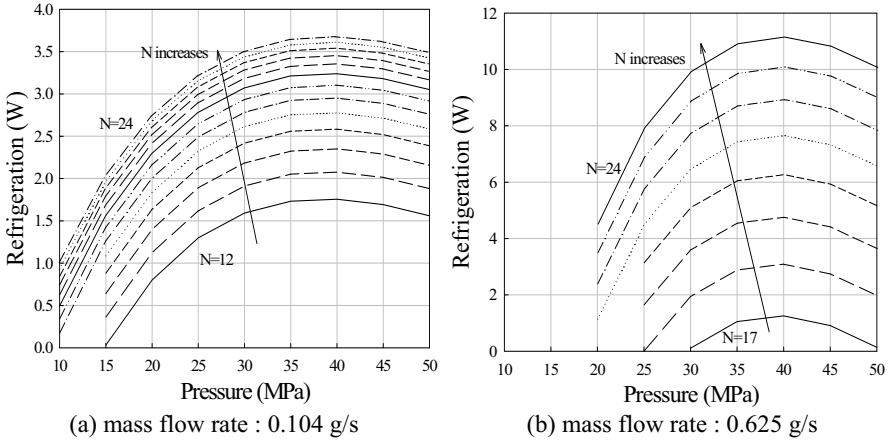


Figure 3. Refrigeration of the type (I)

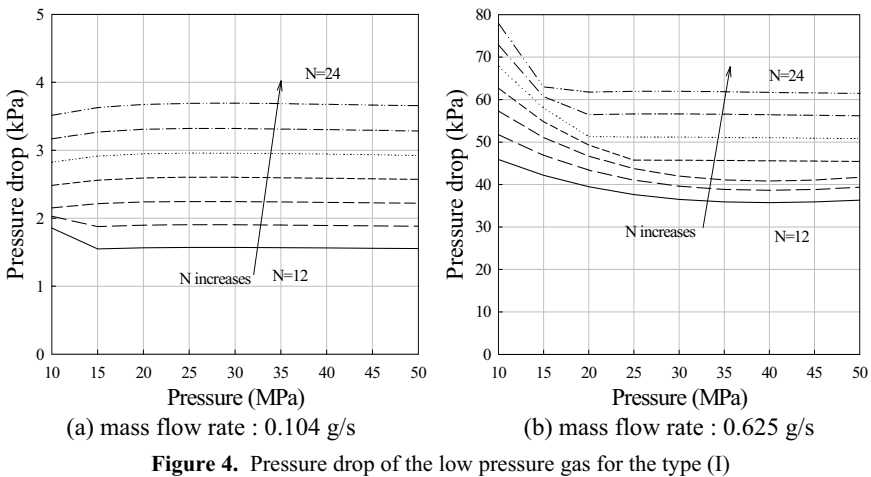


Figure 4. Pressure drop of the low pressure gas for the type (I)

## RESULTS AND DISCUSSION

Liquefied yield is an important parameter in the evaluation of the performance of a J-T refrigerator, as it affects the effectiveness of the heat exchanger. Effectiveness of the heat exchanger depends on the mass flow rate, heat transfer area, heat transfer characteristics, and thermodynamic properties of the gas. Typically, increases of the mass flow results in the decreases of the effectiveness of the heat exchanger.

Figure 3 present the effect of the number of wraps (N) and pressure of the gas on the refrigeration. With an increase in the number of wraps, the overall length of the heat exchanger increases and the refrigeration increases. The refrigeration increases as the supply pressure of the gas increases up to 40 MPa. The refrigerator with the larger mass flow rate has the higher refrigeration. But the minimum number of wraps to get the refrigeration increases as the mass flow rate increases. The refrigeration is not linearly proportional to the mass flow rate due to changes in the effectiveness of the heat exchanger.

The performance of a J-T refrigerator depends on the pressure drop of the gas. In the passage for the high pressure gas, a relatively small pressure drop occurs, and the effects of the pressure drop on the performance are small. Figure 4 shows the effects of the number of wraps and pressure of the supply gas on the pressure drop of the low-pressure gas.

The results show that the pressure drop increases as the number of wraps increases. The refrigerator with the larger mass flow rate has the higher pressure drop. The supply pressure of the gas does not affect the pressure drop. In the case of a low pressure gas supply, a large pressure drop can occur due to a change of the physical properties of the gas.

Figure 5 shows the effects of the mass flow rate on the pressure drop of the low pressure gas and the temperature of the gas after the J-T expansion for a gas that is supplied at a fixed pressure of 40 MPa and 295 K. As shown, the heat exchanger pressure drop increases as the mass flow rate of the gas increases, and also increases as the number of the heat exchanger wraps is increased. The J-T cooling temperature, shown on the right of Fig. 5, increases in proportion to the mass flow rate and the pressure drop. Note that the refrigerator with the smaller number of wraps of the heat exchanger tends to reach a lower temperature. However, with an increase in the mass flow rate, such a refrigerator may not reach a temperature of 80 K or less. When our type (I) J-T had just 12 wraps, a sudden change of the temperature occurred due to a decrease of the effectiveness of the heat exchanger at a higher mass flow.

Figure 6 shows the pressure-enthalpy diagram for the refrigerator for different numbers of wraps of the finned tube. It is obvious that the pressure drop of the high pressure gas is small. With an increase in the number of wraps, the entering temperature of the high pressure gas decreases due to an increase in the effectiveness of the heat exchanger, but the J-T exit temperature of the low pressure gas increases. The liquefied yield increases as the number of wraps increases.

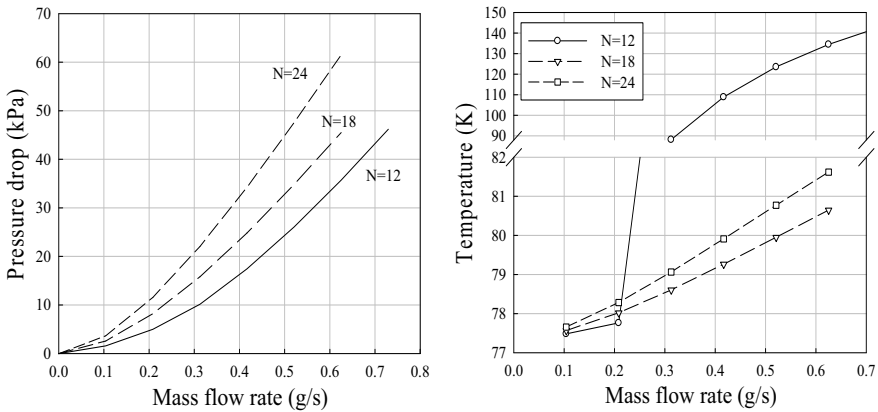


Figure 5. Pressure drop and temperature of the type (I)

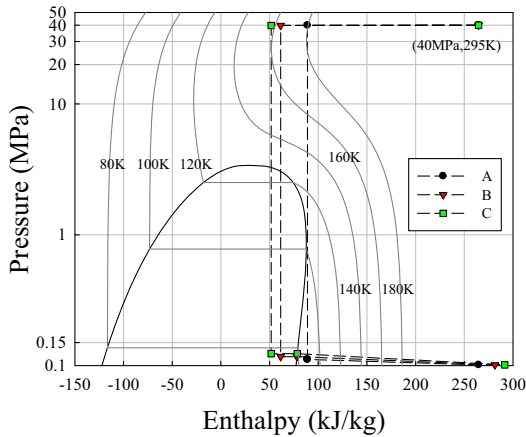
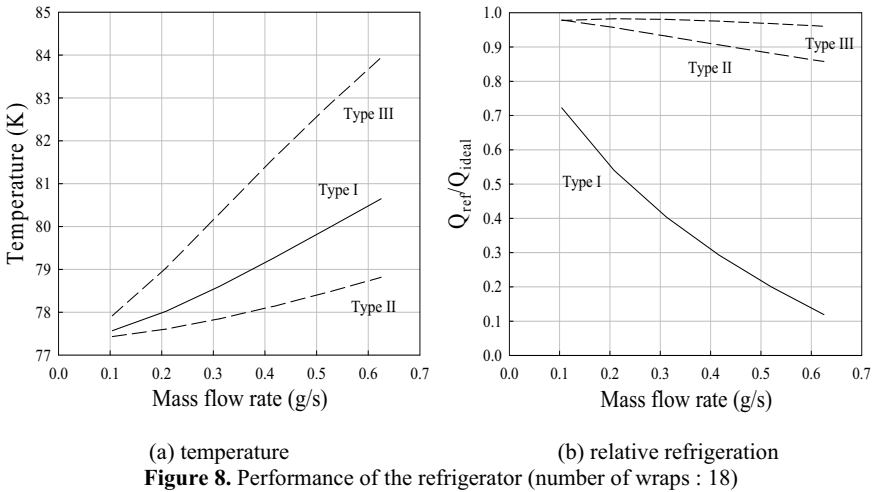
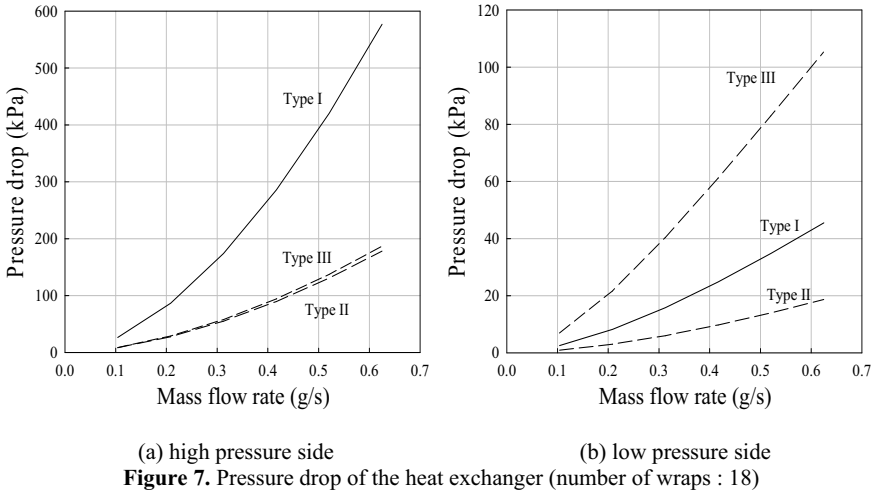


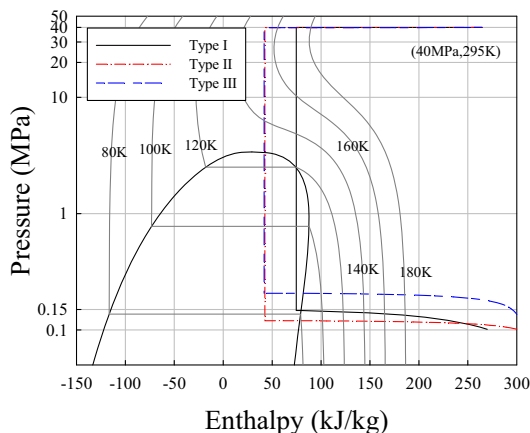
Figure 6. P-h diagram of the type (I) with the mass flow rate of 0.313 g/s. (Number of wraps A : 12, B : 18, C: 24)



For the case A with 12 wraps, the temperature of the exhaust gas from the passage of the high pressure gas is 180 K, the gas is not liquefied at the exit of the J-T nozzle. It is obvious that there is a criteria for the effectiveness of the heat exchanger that is required to insure liquefaction of the gas. Figure 7 show pressure drops of the high pressure and low pressure side for the type (I), (II) and (III) heat exchangers when the supply pressure of the gas is 40 MPa and the heat exchanger has 18 wraps of the finned tube. For the high pressure side, types (II) and (III) have a smaller pressure drop than that of type (I); this is because type (II) and (III) have two passages for high pressure gas, and the mass flow rate of the gas per passage is half of that of type (I).

For the low pressure side, the type (III) has a larger pressure drop than type (I), and type (II) has a smaller pressure drop than type (I). The pressure drop depends on the overall length of the heat exchanger and the flow area. The overall length of the heat exchanger of type (III) is double that of the types (I) and (II). Type (II) has twice the flow area on the low pressure side as compared to types (I) and (III).

Figure 8 shows the effects of the configuration of the heat exchanger on the gas temperature after the J-T expansion and the relative amount of refrigeration. The results show that the refrigerator with type (II) heat exchanger has the lowest temperature with the same mass flow rate, but type (III) exceeds a temperature of 80 K when a small mass flow rate is used.



**Figure 9.** P-h diagram for the J-T refrigerator  
(mass flow rate : 0.625 g/s, number of wraps : 18)

A J-T refrigerator with an ideal heat exchanger of 100% effectiveness generates the maximum amount of refrigeration. The maximum refrigeration reaches 26 W when the mass flow rate exceeds 0.6 g/s. The configuration of the heat exchanger affects the effectiveness. The relative refrigeration decreases as the mass flow rate increases as shown in Figure 8.

Type (I) has a rapid decrease of relative refrigeration, while types (II) and (III) have small decreases of relative refrigeration when the mass flow increases. When a refrigerator has a large mass flow rate of gas, type (III) has the highest refrigeration.

Figure 9 shows the pressure-enthalpy diagram for the different configurations of the heat exchangers. Types (II) and (III) have similar temperatures for the exhaust of the high pressure gas. It is obvious that the type (I) has small effectiveness of the heat exchanger, and type (II) and (III) have similar effectiveness of the heat exchanger. The large pressure drop of the type (III) results in the high temperature of the gas after expansion.

Finally, a refrigerator has a higher refrigeration when the overall length of the heat exchanger increases and the mass flow rate increases. In the case when two passages for the high pressure gas were employed for the J-T heat exchanger, higher refrigeration could be achieved than with a single passage for the high pressure gas. For rapid cooling, two passages for the high pressure gas is a very helpful design attribute for a J-T refrigerator.

The refrigerator with heat exchanger of type (II) has the lowest temperature and highest refrigeration when a high mass flow rate of gas is utilized.

## SUMMARY

In the present study, the effectiveness-NTU approach was adopted to predict the thermodynamic behavior of heat exchangers for J-T refrigerators using nitrogen gas, and the performance of J-T refrigerators with single and two-flow type recuperative heat exchangers was investigated.

The results show the effects of the number of wraps of the finned tube, the mass flow rate, and the supply pressure of the gas on the performance of the refrigerators. The refrigerator has higher refrigeration when the overall length of the heat exchanger increases and the mass flow rate increases. But, with an increase in the mass flow rate and the number of wraps, the refrigerator could not reach a temperature of 80 K or less.

For cases where two passages for the high pressure gas were employed for the J-T heat exchanger, higher refrigeration could be achieved than with a single passage for the high pressure gas. For rapid cooling, two passages for the high pressure gas is a very helpful design attribute.

### ACKNOWLEDGMENT

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